Electro-Thermal-Mechanical Simulation Capability

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The purpose of this project is to research and develop numerical algorithms for 3-D electro-thermal-mechanical (ETM) simulations. LLNL has long been a world leader in the area of computational solid mechanics, and recently several solid mechanics codes have become "multi-physics" codes with the addition of fluid dynamics, heat transfer, and chemistry. However, these multi-physics codes do not incorporate the electromagnetics that is required for a coupled ETM simulation. There are numerous applications for an ETM simulation capability, such as explosively driven magnetic flux compressors, electromagnetic launchers, inductive heating and mixing of metals, and micro-electromechanical systems (MEMS).

Project Goals

A coupled ETM simulation is a simulation that solves, in a self-consistent manner, the equations of electromagnetics (primarily statics and diffusion), heat transfer (primarily conduction), and nonlinear mechanics (elastic-plastic deformation, and contact with friction). Our goal is to add electromagnetics to two existing mechanics codes, ALE3D and Diablo. ALE3D is a heavily used Arbitrary-Lagrangian-Eulerian hydrodynamics code; Diablo is an implicit Lagrangian thermal-mechanics code currently under development.

Our objective is to develop a novel simulation capability that is not available commercially or from the other national laboratories. With this capability, LLNL will have an unprecedented ability to simulate, design, and optimize ETM systems.

Relevance to LLNL Mission

This project is aligned with LLNL's core competency in simulation science and engineering. It contributes to the mission to enhance/extend the simulation capabilities and specifically addresses the need for simulation capability in the area of energy manipulation. A robust ETM simulation capability will enable LLNL physicists and engineers to better support current DOE programs, and will prepare LLNL for some very exciting long-term DoD opportunities.

FY2007 Accomplishments and Results

FY2007 was our final six-month effort with emphasis on code enhancements, verification, validation, publications, and initiation of follow-on activities. The two primary code enhancements were the development of an RLC circuit model and the incorporation of a multigrid solver.

The RLC circuit model is used to model capacitor banks and associated cables and pulse-shaping hardware. With this circuit model it is not necessary to know the applied voltage *a-priori*; instead the applied voltage is computed by solving the ETM PDE's and the RLC circuit model self-consistently.

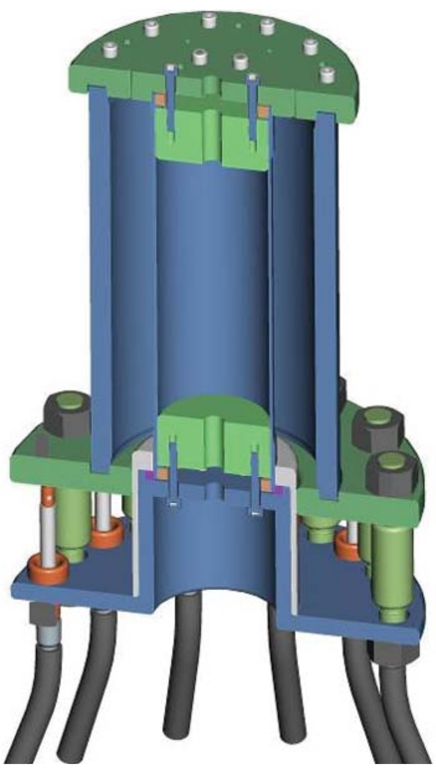

Figure 1. CAD image of the coaxial load experiment. The image shows the steel outer tube, the aluminum inner tube, the torlon bolts,and the coaxial cables.

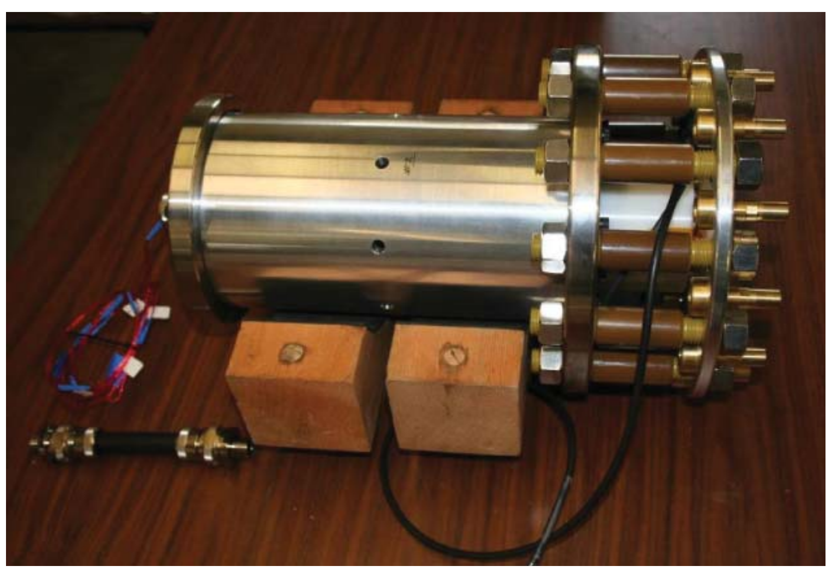

Figure 2. Photograph of the coaxial load experiment test fixture.

We incorporated a multigrid solver for the curl-curl equations. The solver has numerous parameters and requires auxiliary mesh information such as element connectivity and nodal coordinates. The end result is that the solver is approximately 10x faster for typical problems of interest, and has better scalability.

The primary code validation task was designing and executing a coaxial load experiment and comparing experimental data to computational simulations. A CAD image of the test fixture is shown in Fig. 1 and a photograph is shown in Fig. 2. A sequence of tests were executed, with the initial tests at low current such that the deformation of the inner tube was small and the material response was linear. Subsequent tests used larger current with significant plastic deformation of the inner tube. An example result is shown in Fig. 3. Overall, the simulation agreed quite well with the experimental data for early times (t < 100 µs), showing that there are no major errors in the numerical algorithms or the software implementation.

The final experiment was with a 0.030-in. inner tube with slots. The purpose of the slots is twofold: they make the problem become a fully 3-D problem, and the deformation of the metal should be significant. In fact, we expect a complete destruction of the tube. The simulation result is shown in Fig. 4; the experimental data is still being examined.

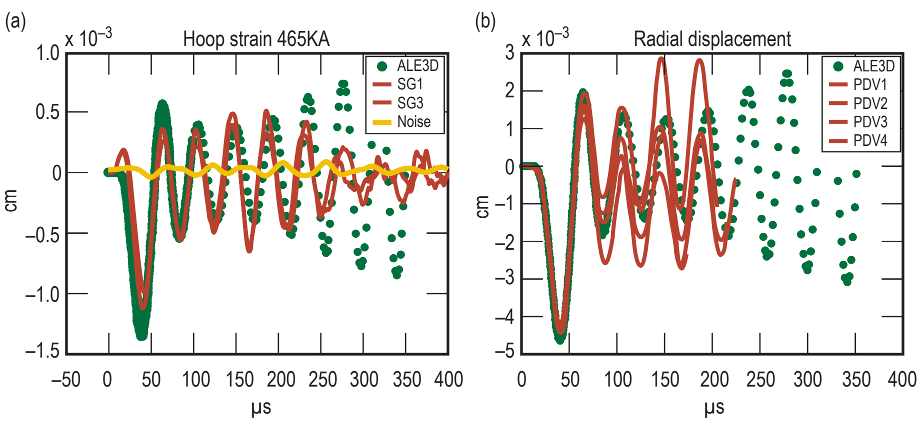

Figure 3. Comparison of experimental data with computed results for the 465-kA, 0.060-in. tube shot. (a) Hoop strain measure by the two strain gauges; (b) radial displacement measure by the four PDV gauges. Note that the current peaks at 30 µs and returns to zero at 100 µs, so it is the early time data that tests the coupling of electromagnetics and hydrodynamics. The late time data is determined solely by momentum and material models.

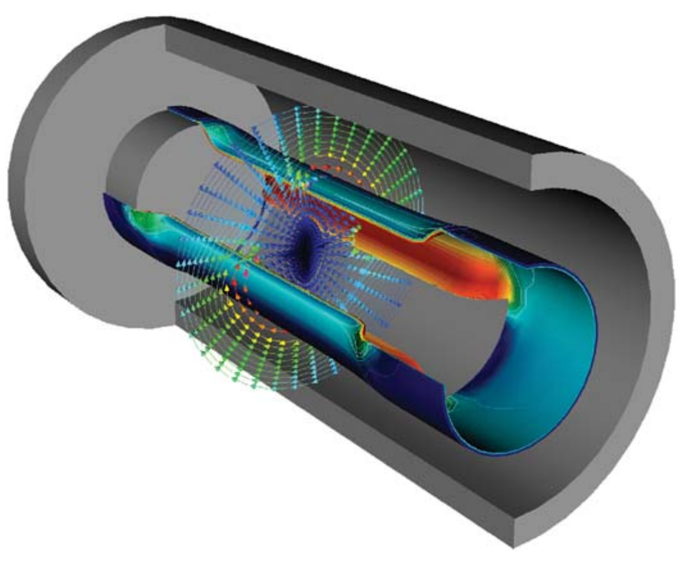

Figure 4. Simulation of a coaxial load test shot. This image shows both the magnetic flux density (vectors) and the current density (pseudo color). This particular shot had slots cut in the inner tube so that it was a fully 3-D problem; axial symmetry did not apply.

Related References

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2. Rieben, R., and D. White, "Verification of High-Order Mixed Finite Element Solution of Transient Magnetic Diffusion Problems," *IEEE Trans. Magnetics*, **42**, 1, pp. 25-39, 2006.
3. White, D., and B. Fasenfest, "Performance of Low-Rank QR Approximation of the Finite Element Biot-Savart Law," *IEEE Trans. Magnetics*, **43**, 4, pp. 1485-1488, April 2007.
4. White, D., R. Rieben, and B. Wallin, "'Coupling Magnetic Fields and ALE Hydrodynamics for 3D Simulations of MFCG's," *IEEE International Conference on Megagauss Magnetic Field Generation*, Santa Fe, New Mexico, November 5-10, 2006.
5. Solberg, J. M., D. A. White, and R. N. Rieben, "A Mortar-Based Method for Zero-Conductivity Regions in a Coupled Electro-Thermal-Mechanical Simulation Code," *7th World Congress on Computational Mechanics*, Los Angeles, California, 2006.

FY2008 Proposed Work

We have proposed future experiments using the same coaxial test fixture to validate kink instabilities, bucking instabilities, and electrical contacts.

Based on our success with this project we were asked to participate in the Bore Life Consortium of the Office of Naval Research (ONR) Railgun S&T Program. The consortium is tasked with gaining an understanding of phenomena that affect railgun bore life, such as thermal ablation, gouging, and arcing. We will continue to develop the ETM simulation capability, to use the ETM simulation capability to model the notional ONR railgun, and to investigate novel materials and diagnostics.